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Dispersion of Leachate in Aquifers

PURPOSE: Contaminated dredged material is often placed in confined disposal facilities (CDFs) designed and operated to control environmental impacts of the disposed sediment. A CDF is a diked enclosure having structures that retain dredged material solids. When contaminated dredged material is placed in a CDF, contaminants may be mobilized to form leachate that may be transported to the site boundaries by seepage. The purpose of the research presented here is to examine the components of steady-state leachate attenuation in aquifers and to develop predictive equations of the attenuation for use in a screening tool being developed for the upland testing manual (USACE 2003). The main factors affecting leachate transport and dilution through the saturated zone of an aquifer are evaluated to develop a guidance procedure to assist in decision making regarding the use of leachate controls in the CDF. The U.S. Environmental Protection Agency's (EPA's) MULTIMED model is used to develop predictive equations for the effects of recharge and lateral and vertical dispersion processes on center-line concentrations in the aquifer. Results show that the effects of these processes can be predicted independently. Relationships were developed to estimate the attenuation factor for each process. An equation for center-line leachate concentration using attenuation factors was developed to predict peak leachate exposure for decision making.

BACKGROUND: The main reason for the study described herein is to develop a set of simple equations that can be used in a procedure to screen the leachate pathway for unacceptable exposure to contaminants as presented in the upland testing manual (USACE 2003). Section 404 of the Clean Water Act of 1972, as amended, the National Environmental Policy Act of 1969, the U.S. Army Corps of Engineers (USACE) management strategy for dredged material disposal (Francingues et al. 1985), and the USACE/USEPA technical framework for evaluating the environmental effects of dredged material management alternatives (USACE/USEPA 1992) require the evaluation of the confined disposal alternative for dredged material to include groundwater impacts. The leachate pathway is depicted in Figure 1.

Leachate seeping into the groundwater from dredged material placed in a CDF is produced by several potential sources: gravity drainage of the original pore water and ponded water, vadose zone moisture, inflow of groundwater, and infiltration of rainwater and snowmelt. Thus, leachate generation and transport in and out of the CDF depend on many site-specific and sediment-specific disposal factors. Leachate concentrations percolating from the CDF are attenuated as they are transported through the vadose zone (Schroeder and Aziz 2002). When contaminants reach the saturated zone, they are transported due to the hydraulic gradient in this zone. In the saturated zone, contaminant concentrations are a function of the dispersion characteristics of the aquifer, the relative rates of leachate percolation and groundwater flow, and the aquifer recharge rates.

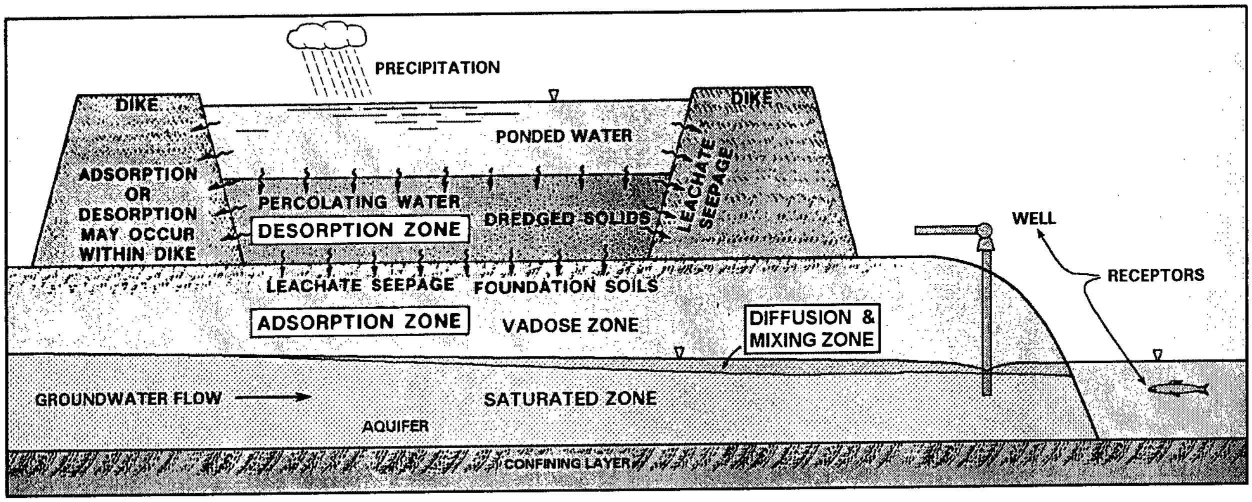

Figure 1. Model of dredged material leachate pathway

The concentration of leachate to which a receptor is exposed is further impacted by diffusion or mixing as the leachate is transported from the CDF locale to the receptor through the coarse-grained layers of an aquifer. In effect, the contaminant concentration of the leachate is diluted by the groundwater flow. Attenuation by adsorption to organic matter and interactions with fine-grained materials will also occur in the aquifer, but the effect is generally small due to low concentrations of organic and clayey materials in the main regions of saturated groundwater flow. However, attenuation of leachate concentration in the saturated zone is seriously impacted by groundwater recharge through the vadose zone. Hence, leachate at the receptor is affected by the groundwater flow rate and recharge rate, the dominant hydraulic processes between the CDF and the receptor. Areas with high groundwater velocities provide greater dilution of the leachate plume, but spread the leachate plume more quickly. These and other important parameters are discussed below.

The quantity and quality of the leachate percolating out of a CDF through the vadose zone and eventually into the saturated zone is a function of CDF design and operation, the contaminant, and the properties of the vadose zone. Leachate flow through the vadose zone can be modeled using the HELPQ model (Schroeder and Aziz 1999). Leachate quantity increases with the area of the CDF and decreases with increased application of best management practices. Dewatering and consolidation of the dredged material decrease the pressure head that drives drainage through the CDF and decrease the hydraulic conductivity of the dredged material, both serving to decrease leachate production.

Liners and drains are the primary control features for leachate. Liners can greatly restrict leachate flow rates from CDFs and act to divert leachate to offsite drains that collect the leachate and route it to a treatment facility. These control measures prevent nearly all of the leachate from reaching any of the receptors.

INTRODUCTION: Leachate that reaches the saturated zone is subjected to immediate mixing and dilution with the groundwater. The rate of dilution immediately below the CDF and down-gradient depends on the relative rates of leachate infiltration into the groundwater flow and aquifer properties such as hydraulic conductivity, thickness, porosity, and dispersivity. Additionally,

aquifer recharge due to rainfall infiltration provides additional leachate dilution downstream of the facility. The attenuation of leachate in the aquifer is a three-dimensional solute transport process that is represented by

$$D_x \frac{\partial^2 C}{\partial x^2} + D_y \frac{\partial^2 C}{\partial y^2} + D_z \frac{\partial^2 C}{\partial z^2} - V \frac{\partial C}{\partial x} = \frac{\partial C}{\partial t} + \frac{V_r C}{B\theta} \tag{1}$$

where x, y, and z are the longitudinal, lateral, and vertical directions, respectively [L]; C is the dissolved concentration of the contaminant [M/L^3]; D_x, D_y, and D_z are the dispersion coefficients in the x, y and z directions, respectively [L^2/T]; V is the uniform groundwater velocity in the x-direction [L/T]; t is the elapsed time [T]; V_r is the net recharge percolating directly into the contaminant plume [L/T]; B is the thickness of the saturated zone [L]; and θ is the effective porosity [dimensionless].

The flow domain is regarded as semi-infinite in the x-direction ($0 < x < \infty$), infinite in the y-direction ($-\infty < y < \infty$), and finite in the z-direction ($0 < z < B$). A schematic of the flow domain in Figure 2 shows the coordinate system, and the facility, receptor, and variable definitions.

There are a number of numerical models that can be used to simulate this process, such as MEPAS (Whelan et al. 1996), MULTIMED (Salhotra et al. 1993), AT123D (Yeh 1981), and the Department of Defense Groundwater Modeling System (GMS), to name a few. MULTIMED is used as the computer model for the evaluation of the impact of aquifer properties on leachate concentrations at the source because it has been widely used for similar applications and completely describes the dominant processes. In solving Equation 1, MULTIMED uses two boundary conditions in each of the x, y, and z directions and an initial condition.

The source is defined as the downgradient edge of the waste disposal unit and is used as the upstream boundary condition. The MULTIMED model allows a choice between two boundary conditions with respect to the distribution of contaminant along the vertical plane at the source (Salhotra et al. 1993). The first boundary condition specifies the contaminant concentration as a Gaussian distribution in the lateral direction and uniform over the source penetration depth H.

Mathematically, this boundary condition can be expressed as

$$C(0,y,z,t) = \begin{cases} C_o \exp\left(\dfrac{-y^2}{2\sigma^2}\right) & 0 \le z \le H \\ 0 & H < z \le B \end{cases} \tag{2}$$

in which C_o [M/L^3] is the maximum dissolved concentration of the solute at the source and occurs at the center of the Gaussian distribution. The standard deviation σ is a measure of the source width W normal to the mean flow direction and is written as

$$\sigma = \frac{W}{6} \tag{3}$$

which implies that 99.86 percent of area under the Gaussian source falls within the width of the facility.

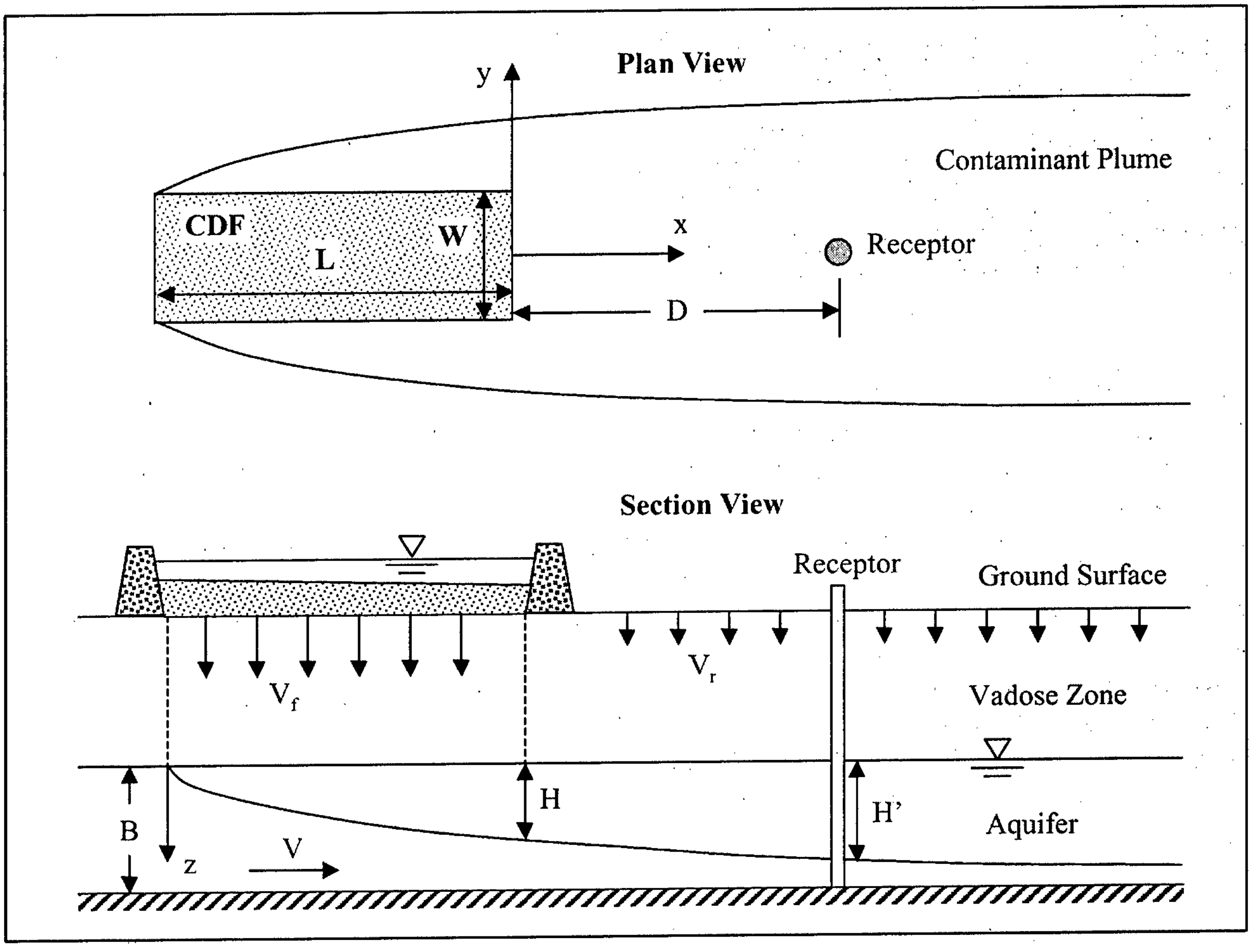

Figure 2. Schematic of facility, receptor, and contaminant plume

The concentration at the center of the Gaussian distribution is determined based on the dilution of the contaminant concentration entering the saturated zone. MUMLTIMED uses the mass balance of contaminants to compute the source concentration C_o as (Salhotra et al. 1993):

$$C_o = \frac{A_f V_f}{(A_f V_f + \sqrt{2\pi} V\theta H\sigma)} C_f \tag{4}$$

where A_f is the area of the facility [L^2]; V_f is the percolation rate from the facility [L/T]; C_f is the concentration of leachate percolating from vadose zone [M/L^3]; and H is the source thickness [L].

The thickness of the source represents the depth penetration below the downstream end of the facility that is impacted by the leachate. The depth of penetration is impacted by the vertical

advection of water as it moves beneath the facility and by the vertical dispersion in the saturated zone. This thickness is given by Salhotra et al. (1993) as

$$H = (2\alpha_z L)^{1/2} + B\left[1 - \exp\left(-\frac{LV_f}{V\theta B}\right)\right] \tag{5}$$

where α_z is the vertical dispersivity [L] and L is the length of the facility [L].

The first term on the right-hand side of Equation 5 represents the contribution of vertical dispersion to the depth of penetration, and the remaining terms represent the effect of advection. Clearly, if the source thickness H exceeds the thickness of the saturated zone B, then H is set equal to B. In this case, the entire saturated zone downgradient of the facility is completely mixed and vertical dispersion becomes insignificant in the transport process along the vertical plane of symmetry.

The steady-state solution for the semi-infinite domain assumes zero concentration at an infinite distance from the source, i.e. the background concentrations are zero.

$$C(\infty, y, z) = 0 \tag{6}$$

$$C(x, \pm\infty, z) = 0 \tag{7}$$

The final boundary conditions assume that there is no contaminant flux across the upper and lower boundaries of the saturated zone. These boundary conditions are represented as

$$\frac{\partial C}{\partial z}(x,y,0) = 0 \tag{8}$$

$$\frac{\partial C}{\partial z}(x,y,B) = 0 \tag{9}$$

The steady-state concentration along the plume centerline can be expressed as

$$C(x,0,0) = \xi \frac{H}{B} \int_0^\infty \exp\left[-\frac{\sigma^2 u^2}{2} - x\left(\frac{u^2 \mathrm{D}_y}{\mathrm{D}_x} + \frac{V^2}{4\mathrm{D}_x^{\,2}}\right)^{1/2}\right] du \tag{10}$$

where

$$\xi = \frac{2C_o\sigma}{(2\pi)^{1/2}} \exp\left(\frac{Vx}{2\mathrm{D}_x}\right) \tag{11}$$

and u is the integration variable [L^{-1}].

Assumptions used in the analysis are as follows:

1. A single aquifer with uniform thickness is modeled. The saturated porous medium properties are isotropic and homogeneous.
2. The groundwater flow velocity is steady and uniform. This implies that the recharge through the facility and into the groundwater plume is small compared to the natural (regional) flow.
3. No contaminant degradation/transformation or sorption is assumed.
4. The background contaminant concentration in the aquifer is zero.

AQUIFER IMPACT ON LEACHATE. The screening procedure is developed based on the CDF size, saturated flow properties, aquifer properties, recharge rates and receptor location. The main concern of this screening procedure is to determine the peak contaminant concentration reaching the receptor under steady-state conditions. Due to the symmetrical nature of the problem, peak concentrations will occur in the longitudinal direction along the centerline of the facility. Therefore, a receptor located downstream of the facility along the centerline of the facility will experience a higher concentration than all points that are at the same distance away but are not along the centerline. This concentration is represented as a function of several variables.

$$C = f''\left(C_o, D, L, W, B, K, \frac{dh}{dx}, V_f, V_r, \alpha_y, \alpha_z\right) \tag{12}$$

where D is the distance from facility to receptor along centerline of facility [L]; K is the hydraulic conductivity [L/T]; dh/dx is the slope of the water table [L/L]; and α_y is the transverse dispersivity [L].

Equation 12 may be written in dimensionless form as

$$\frac{C}{C_o} = f'\left(\frac{W}{\sqrt{\alpha_y D}}, \frac{B}{\sqrt{\alpha_z L}}, \frac{L}{L+D}, \frac{q_f}{q_s+q_f}, \frac{q_r}{q_s+q_r}\right) \tag{13}$$

where q_s equals $BK(dh/dx)$, which is the groundwater flow per unit width of aquifer [L^2/T]; q_f equals $V_f L$, which is the leachate flow rate downward per unit width of facility [L^2/T]; and q_r equals $V_r D$, which is the groundwater recharge rate per unit width [L^2/T].

Since C_o as given by Equation 4 can be written as a function of $q_f/(q_s + q_f)$, and H as given in Equation 5 is a function of α_z, Equation 13 can be reduced further to

$$\frac{C}{C_o} = F\left(\frac{W}{\sqrt{\alpha_y D}}, \frac{H}{B}, \frac{L}{L+D}, \frac{q_s}{q_s+q_r}\right) \tag{14}$$

The source thickness H refers to the maximum depth of mixing at the downstream edge of the facility and is defined by Equation 5. There are three plausible scenarios for the depth of penetration in relation to the facility and the receptor as depicted in Figure 3.

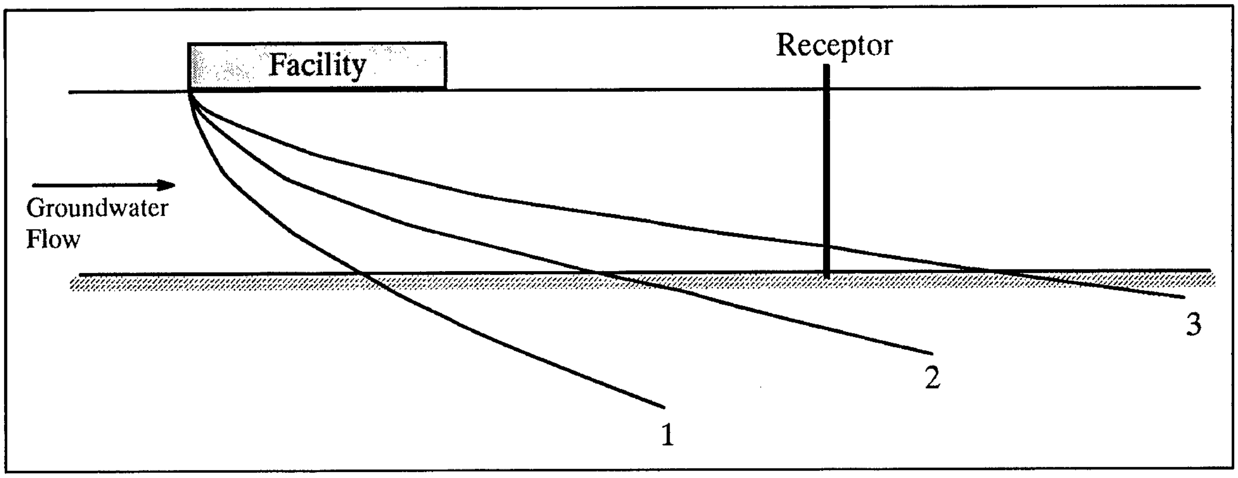

Figure 3. Three possible scenarios for plume vertical penetration

In the scenario labeled 1 in Figure 3, the source thickness is greater than the thickness of the saturated zone implying that complete vertical mixing occurred beneath the facility. In this case, the solution assumes $H = B$, and the plume covers the entire depth of the saturated layer from the downgradient boundary of the facility to the receptor. The contribution of groundwater recharge will simply have a dilution impact on the plume.

The second scenario, represented by the vertical penetration depth of the plume (line 2 in Figure 3), indicates that complete vertical mixing of the saturated zone does not occur beneath the facility. However, complete vertical mixing occurs upstream of the receptor. Vertical dispersion and groundwater recharge serve to force the plume to become completely mixed throughout the depth of the saturated zone before it reaches the receptor. The solution of this scenario is the same as that of case 1, since the entire depth of groundwater flow is enveloped in the plume.

The third and last scenario is the case where complete vertical mixing of the saturated zone occurs downstream of the receptor. This is a case of one or more of the following: thick aquifer, short distance to the receptor, low recharge rate, or small vertical dispersivity. In this case, all parameters of Equation 14 are significant. The thickness of the plume at the receptor H' is defined as

$$H' = \left(2\alpha_z \left(L + D\right)\right)^{1/2} + B\left[1 - \exp\left(-\frac{LV_f + DV_r}{V\theta B}\right)\right] \tag{15}$$

The actual relationship described by Equation 14 is derived using MULTIMED simulations. The impact of aquifer properties on the leachate concentration at the receptor is evaluated using MULTIMED to develop a screening procedure. The model could be run for the site-specific conditions if increased accuracy in the predictions were needed to pass the screening.

In order to determine steady-state contaminant concentrations at the receptor, MULTIMED was used to simulate the effects of the parameters of Equation 14 on the leachate concentration at the receptor. Simulation parameters may be divided into facility (L, W, C_f, q_f), aquifer (B, K, dh/dx, α_y, α_z, q_s), and recharge (V_r and D). Table 1 summarizes data used in the simulation. The

selection of values for the simulations was designed to isolate the effects of the attenuation processes as explained in subsequent sections.

Table 1
MULTIMED Simulation Data

Run No.	V_f (m/yr)	V_r (m/yr)	*L* (m)	*W* (m)	*K* (m/yr)	*dh/dz* (m/m)	*D* (m)	α_y (m)	α_z (m)	*B* (m)	*H* (m)	*H'* (m)	C/C_o
1	0.0252	0.2	500	10	31500	0.003	100	1.89	1.55	15	39.5	43.3	0.093
2	0.0252	0.2	500	20	31500	0.003	100	1.89	1.55	15	39.5	43.3	0.183
3	0.0252	0.2	500	50	31500	0.003	100	1.89	1.55	15	39.5	43.3	0.416
4	0.0252	0.2	500	75	31500	0.003	100	1.89	1.55	15	39.5	43.3	0.559
5	0.0252	0.2	500	100	31500	0.003	100	1.89	1.55	15	39.5	43.3	0.663
6	0.0252	0.2	500	250	31500	0.003	100	1.89	1.55	15	39.5	43.3	0.897
7	0.0252	0.2	500	500	31500	0.003	100	1.89	1.55	15	39.5	43.3	0.961
8	0.0252	0.2	500	750	31500	0.003	100	1.89	1.55	15	39.5	43.3	0.974
9	0.0252	0.2	500	1000	31500	0.003	100	1.89	1.55	15	39.5	43.3	0.979
10	0.7560	0	10	447	31500	0.003	5	0.01	1.55	80	5.6	6.9	0.908
11	0.2205	0	30	894	31500	0.003	20	0.01	1.55	70	9.7	12.1	0.838
12	0.1181	0	40	1265	31500	0.003	40	0.01	1.55	50	11.2	15.8	0.742
13	0.0756	0	50	1673	31500	0.003	70	0.01	1.55	40	12.5	19.3	0.649
14	0.0551	0	60	2000	31500	0.003	100	0.01	1.55	35	13.7	22.3	0.602
15	0.0354	0	80	2828	31500	0.003	200	0.01	1.55	30	15.8	29.5	0.564
16	0.0630	0	90	3464	31500	0.003	300	0.01	1.55	60	16.8	34.8	0.431
17	0.0851	0	100	4000	31500	0.003	400	0.01	1.55	90	17.7	39.5	0.394
18	0.0430	0	110	4472	31500	0.003	500	0.01	1.55	50	18.5	43.5	0.406
19	0.0071	0.005	500	250	266667	0.0001	100	1.89	1.55	15	39.5	43.3	0.908
20	0.0107	0.01	500	250	160000	0.00025	100	1.89	1.55	15	39.5	43.3	0.911
21	0.0142	0.05	500	250	106667	0.0005	100	1.89	1.55	15	39.5	43.3	0.903
22	0.0178	0.1	500	250	66667	0.001	100	1.89	1.55	15	39.5	43.3	0.902
23	0.0252	0.2	500	250	31511	0.003	100	1.89	1.55	15	39.5	43.3	0.897
24	0.0284	0.5	500	250	21333	0.005	100	1.89	1.55	15	39.5	43.3	0.881
25	0.0320	0.75	500	250	12000	0.01	100	1.89	1.55	15	39.5	43.3	0.874
26	0.0356	1	500	250	2667	0.05	100	1.89	1.55	15	39.5	43.3	0.868
27	0.0444	2	500	250	1667	0.1	100	1.89	1.55	15	39.5	43.3	0.841
28	0.0567	0	10	447	31500	0.003	5	0.01	1.55	6	5.6	6.8	0.969
29	0.0347	0	30	894	31500	0.003	20	0.01	1.55	11	9.7	12.5	0.933
30	0.0331	0	40	1265	31500	0.003	40	0.01	1.55	14	11.2	15.8	0.853
31	0.0284	0	50	1673	31500	0.003	70	0.01	1.55	15	12.5	19.3	0.850
32	0.0315	0	60	2000	31500	0.003	100	0.01	1.55	20	13.8	22.3	0.718
33	0.0189	0	80	2828	31500	0.003	200	0.01	1.55	16	15.8	29.5	0.985
34	0.0294	0	90	3464	31500	0.003	300	0.01	1.55	28	16.7	34.8	0.603
35	0.0331	0	100	4000	31500	0.003	400	0.01	1.55	35	17.6	39.4	0.513
36	0.0361	0	110	4472	31500	0.003	500	0.01	1.55	42	18.5	43.5	0.454

Lateral Dispersion. The rate at which the contaminant spreads in the lateral direction is a function of the lateral dispersivity. The magnitude of lateral dispersion is a function of the distance that the plume travels, and the reduction of centerline concentration due to lateral dispersion is a function of the facility width. The results of MULTIMED simulation runs 1 through 9 with constant recharge and vertical dispersion are shown in Figure 4 to evaluate the impact of lateral dispersion. Figure 4 clearly indicates that as the width of the facility increases, with all other variables remaining the same, the concentration at the receptor increases and approaches the source concentration as W approaches infinity. Similarly, for narrow facilities (small W) the concentration at the receptor is smaller. Figure 4 also indicates that the increase in D has the opposite effect as the increase in W. Lateral dispersion has little effect on peak concentrations of leachate at the receptor location except where the distance to the receptor is very long ($D > 10$ W) or where the width of the disposal facility is very narrow ($W < 10$ m). The lateral dispersion factor F_y shown as a solid line in Figure 4, was determined by regression to be

$$F_y = \frac{1}{0.99562 + 8.95506\left(\frac{w}{\sqrt{\alpha_t D}}\right)^{-1.5}} \qquad (16)$$

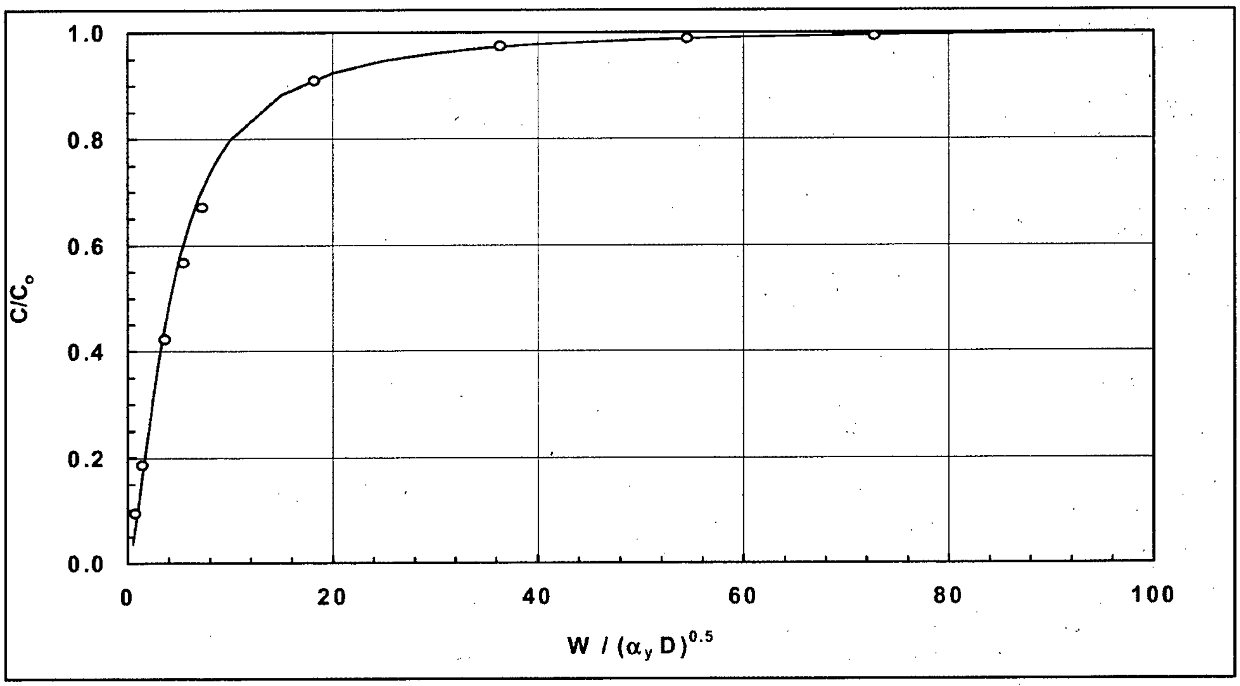

Figure 4. Impact of facility width on centerline concentration (simulation runs 1-9)

Vertical Dispersion. As explained previously, there are three possible cases that should be considered in assessing the impact of vertical dispersion on contaminant concentration at the receptor. These cases are shown in Figure 3 and illustrate the relationship among vertical dispersivity, source thickness, aquifer thickness, and receptor distance from facility. The first case represents the condition where the entire depth of the saturated zone is completely mixed vertically beneath the facility. In this case it is assumed that $H = B$. Since C_o is inversely proportional

to B, the concentration at the receptor is inversely proportional to B. However, the dilution by recharge decreases with increasing aquifer thickness. In this case the vertical dispersion is so large under the facility that it has no impact on the leachate concentration downgradient of the facility. Hence, the vertical dispersion attenuation factor F_z is equal to 1.

The second case shown in Figure 3 is for $H < B < H'$ where H' is the unrestricted thickness of the plume at the receptor as calculated by Equation 15. In this case, complete vertical mixing in the entire saturated zone takes place at a point between the downstream boundary of the facility and the receptor. Vertical dispersion as well as dilution of the plume by the recharge contribute to the concentration at the receptor. The concentration at the receptor is inversely proportional to the aquifer thickness and is independent of the vertical dispersivity. To account for complete mixing occurring between the facility and the receptor, a vertical dispersion attenuation factor F_z can be applied to compute the concentration at the receptor.

$$F_z = \frac{H}{B} \tag{17}$$

where H is calculated using Equation 5.

The third case shown in Figure 3 indicates that complete vertical mixing is not accomplished between the facility and the receptor. In other words, $H < H' < B$. Hence, both vertical dispersion and recharge are significant factors in determining the concentration at the receptor. The concentration at the receptor is not impacted by the aquifer thickness, but is a function of the length of the facility and the distance between the receptor and the facility. In this case the vertical dispersion is not restricted by the aquifer thickness and the impact of vertical dispersion as a function of receptor distance and source length. The results of MULTIMED simulation runs 10 through 18 without recharge and with constant lateral dispersion are shown in Figure 5 to evaluate the impact of vertical dispersion. The vertical dispersion attenuation factor F_z, shown as a solid line in Figure 5, was determined by regression to be

$$F_z = 1.303\sqrt{\frac{L}{L+D}} - 0.1733 \tag{18}$$

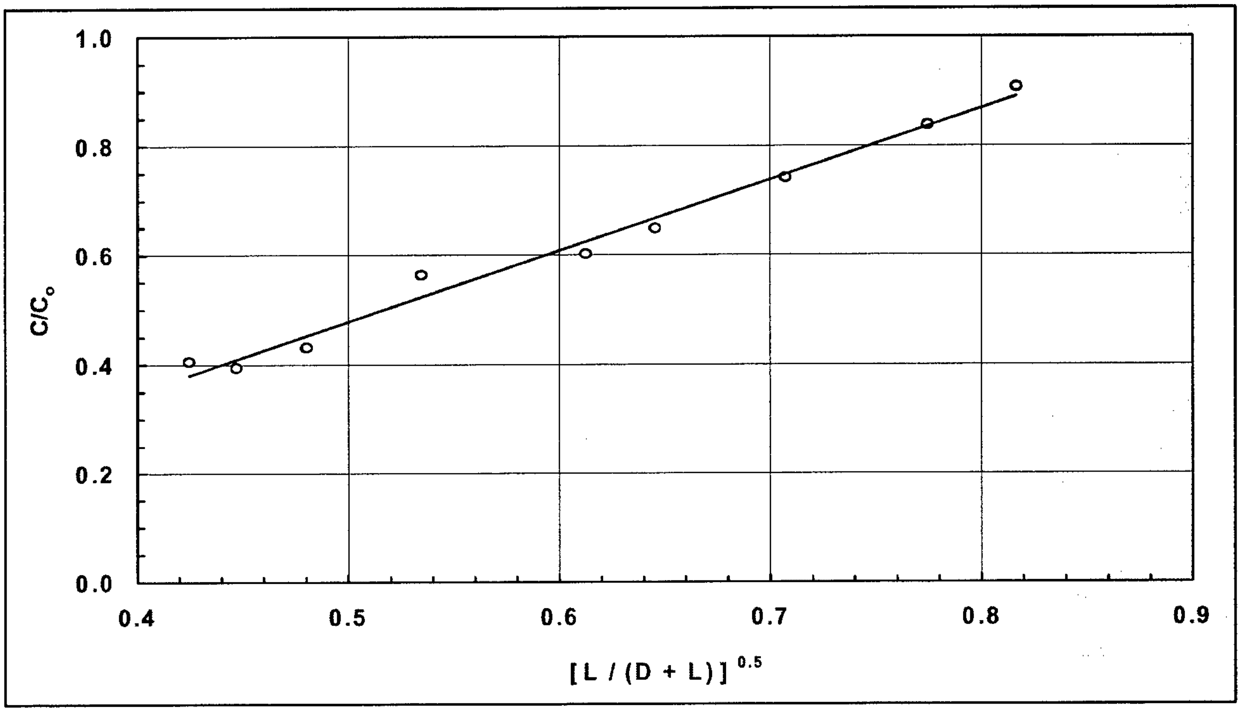

Figure 5. Impact of vertical dispersivity for very thick aquifers on centerline concentrations (simulation runs 10–18)

Impact of Recharge. Groundwater recharge from rainfall infiltration serves to dilute the plume and hence reduces the concentration of the contaminants reaching the receptor. The results of MULTIMED simulation runs 19 through 27 with constant lateral and vertical dispersion are presented in Figure 6 to show the effect of recharge rates on center-line concentrations. The results clearly show that the increase in recharge rates decreases concentrations at the receptor. Aquifer recharge has little effect on peak concentrations of leachate at the receptor location except where the distance to the receptor is very long ($D > 500\ B$), where the thickness of the aquifer is very shallow ($B < 1$ m), or where the groundwater water velocity is very slow ($V <$ 1 m/yr). The recharge attenuation factor F_r, shown as a solid line in Figure 6, was determined by regression to be

$$F_r = 1 - 0.9877\left[\frac{q_r}{q_s\left(H'/B\right) + q_r}\right] \tag{19}$$

Combined Effects. By combining the results of the analysis presented above, a relationship between center-line concentrations at the receptor can be represented as

$$\frac{C}{C_o} = F_y\, F_z\, F_r \tag{20}$$

and is represented graphically in Figure 7 using MULTIMED simulation runs 1 through 36. Note that runs 28 through 36 represent simulations using other values of lateral and vertical dispersion

in combination to provide a verification of the overall approach. Equation 20 or Figure 7 can be used to predict the maximum concentrations expected at the receptor.

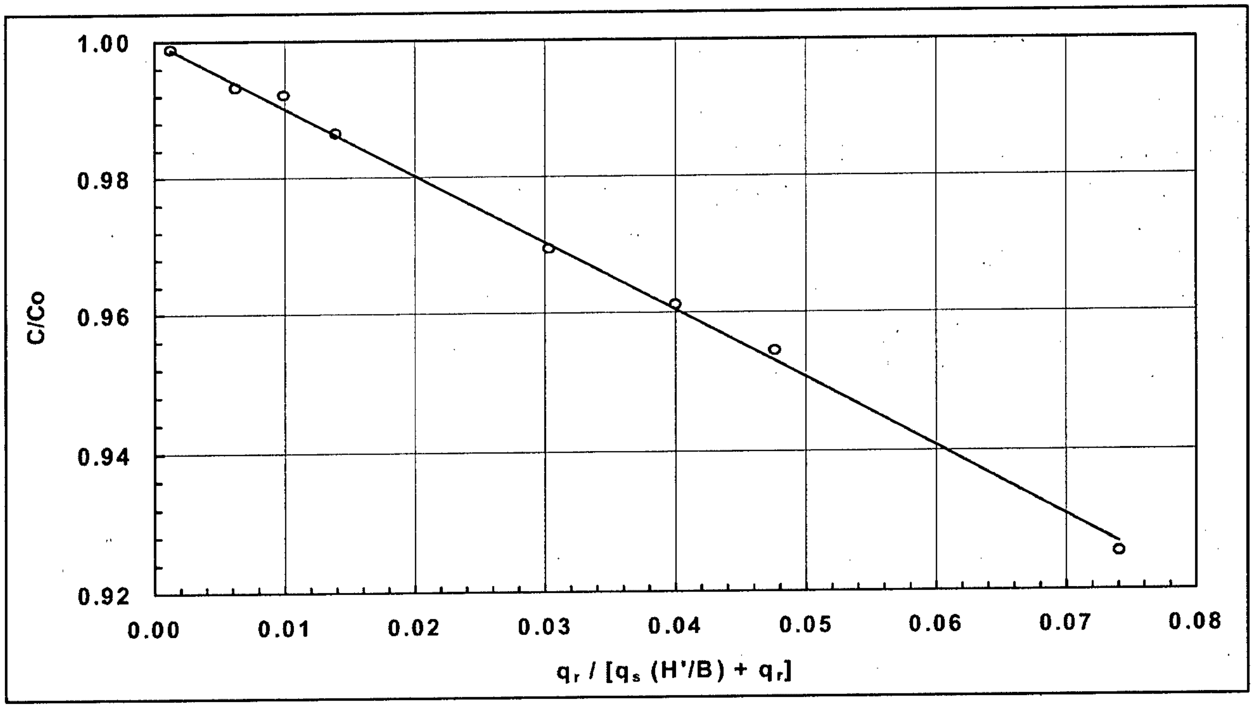

Figure 6. Impact of recharge on center-line concentrations (Simulation runs 19–27)

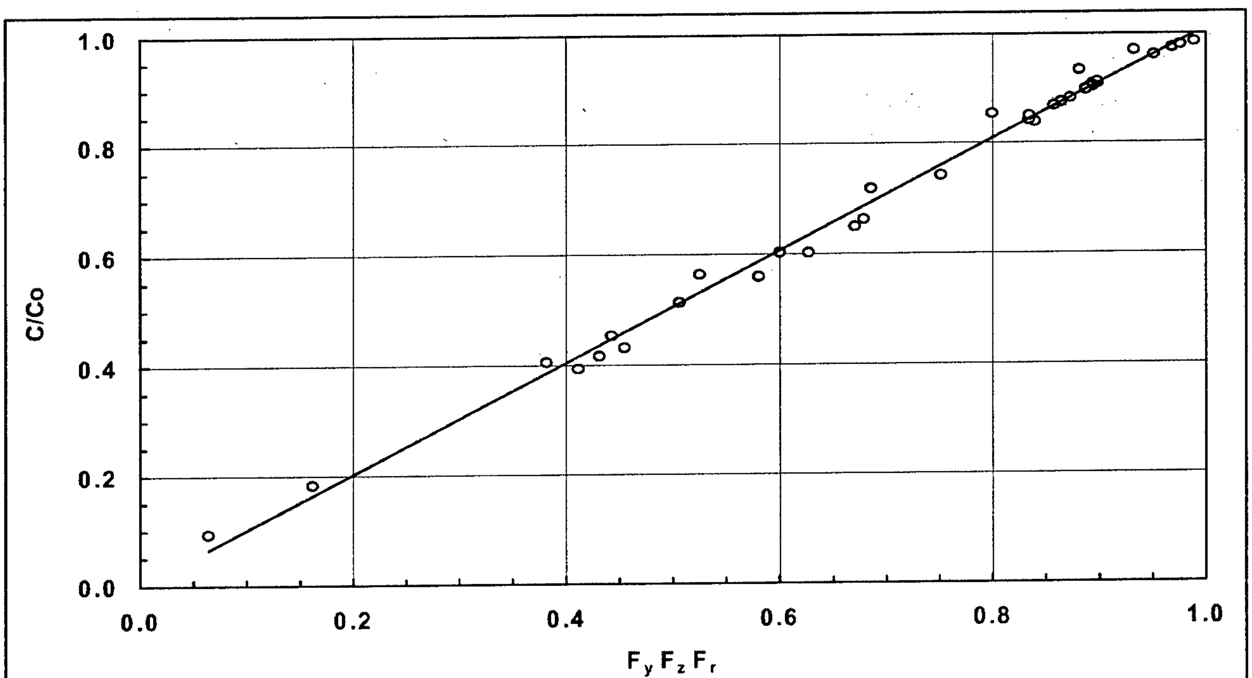

Figure 7. Combined effect of dispersion and recharge (Simulation runs 1–36)

Relating C to the concentration of leachate entering the saturated zone C_f, Equation 4 is substituted into Equation 20 to obtain

$$C = \left(\frac{A_f V_f}{(A_f V_f + \sqrt{2\pi}\, V \theta H \sigma} \right) C_f F_y F_z F_r \tag{21}$$

where B is substituted for H when $H > B$. Equation 21 is an equation that can be readily solved in a screening procedure. It requires the physical parameters of the aquifer and the CDF and the leachate concentration entering the aquifer, which can be obtained from a CDF leachate generation model such as HELPQ (Schroeder and Aziz 1999).

CONCLUSIONS: The research presented above provides predictive equations of leachate attenuation in aquifers for use in the leachate screening procedure presented in the upland testing manual (USACE 2003). Key components of an aquifer such as thickness, recharge rate, and aquifer flow rate and facility-related parameters such as infiltration rate, contaminant concentration, and facility size are used to determine the maximum contaminant concentration at a receptor. The procedure accounts for dilution of the leachate under the disposal facility and downgradient dilution by recharge and lateral and vertical dispersion. The relationships developed in this technical note can be used to estimate the peak concentrations of leachate that would reach the receptor under steady-state conditions.

Peak concentrations of leachate at the receptor location are strongly affected by vertical dispersion, impacting the dilution of the leachate under the disposal facility and downstream of the facility until the leachate plume is fully mixed throughout the entire thickness of the aquifer. The attenuation is greatest in thick aquifers with large groundwater velocities. Lateral dispersion has little effect on peak concentrations of leachate at the receptor location except where the distance to the receptor is very long or where the width of the disposal facility is very narrow. Similarly, peak concentrations of leachate are largely unaffected by aquifer recharge except where the distance to the receptor is very long, where the thickness of the aquifer is very shallow, or where the groundwater water velocity is very slow.

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> Schroeder, P. R. and Aziz, N. M. (2004). "Dispersion of leachate in aquifers," *DOER Technical Notes Collection* (ERDC TN-DOER-C34), U.S. Army Engineer Research and Development Center, Vicksburg, MS. *www.wes.army.mil/el/dots/doer*

REFERENCES

Schroeder, P. R. and Aziz, N. M. (1999). "Contaminant leaching model for dredged material disposal facilities," *ASCE Journal of Environmental Engineering*, 125 (9), 835-844.

Schroeder, P. R., and Aziz, N. M. (2002). "Effect of vadose zone on CDF leachate concentrations," *ASCE Dredging 2002*, Orlando, FL.

Francingues, N. R., Jr., Palermo, M. R., Lee, C. R., and Peddicord, R. K. (1985). "Management strategy for disposal of dredged material: contaminant testing and controls," Miscellaneous Paper D-85-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Salhotra, A. M., Mineart, P, Sharp-Hansen, S., Allison, T., Johns, R., and Mills, W. (1993). "Multimedia exposure assessment model (MULTIMED) for evaluating the land disposal of wastes, Volume 1: Model theory," Rep. prepared for the Environmental Research Laboratory. U.S. Environmental Protection Agency, Athens, GA.

U.S. Army Corps of Engineers. (2003). "Evaluation of dredged material proposed for disposal at island, nearshore, or upland confined disposal facilities — Testing manual," Technical Report ERDC/EL TR-03-1, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

U.S. Army Corps of Engineers/U.S. Environmental Protection Agency (USACE/USEPA). (1992). "Evaluating environmental effects of dredged material management alternatives -- a technical framework," EPA-842-B-92-008, Washington, DC.

Whelan, G., J. P. McDonald, J. P., and Sato, C. (1996). "Multimedia Environmental Pollutant Assessment System (MEPAS): Groundwater pathway formulations," PNNL-10907/UC-630, Pacific Northwest National Laboratory, Richland, WA.

Yeh, G. T. (1981). "AT123D: Analytical transient one-, two-, and three-dimensional simulation of waters transport in the aquifer system," ORNL-5602, Environmental Sciences Division, Oak Ridge National Laboratory, Oak Ridge, TN.